PCT/NZ99/00112
Received 7 June 2000
09/743959
Rec'd PCT/PTO 18 JAN 2001

A Transducer, a Method of Shaping a Transducer, and a Method of Monitoring a Subject

The present invention relates to a novel transducer, a method of monitoring a human or animal subject, and a method of shaping a transducer. More particularly, but not exclusively, the present invention relates to a motion detecting transducer suitable for detecting the state of wakefulness of the driver of an automobile or for detecting the motion of a human (particularly an infant) during sleep.

In some applications where motion is required to be detected it is desirable to have a passive transducer, i.e. a transducer to which no power is supplied. Piezoelectric phenomena provide such an avenue in that the physical motion of the constituent material creates its own voltage.

A piezoelectric transducer is described in US-A-4359726. A polarised piezoelectric foil is contiguously enveloped by a pair of electrodes which are formed on the foil by a process of surface metalisation.

The arrangement of US-A-4359726 suffers from two problems. Firstly, due to the large area of the contiguous electrodes the capacitance between them is high. This high capacitance is a hindrance to the frequency response control of the transducer.

A second problem with the contiguous electrodes is that, if an end user needs to cut the transducer sheet to size to fit the transducer into a desired location (such as a vehicle seat or a baby's bassinet), a short circuit can be created between the electrodes since the piezoelectric film is very thin.

In accordance with a first aspect of the present invention there is provided a transducer comprising a piezoelectric member which deforms in use to provide an electrical output; a first electrode arranged on one side of the

PCT/NZ99/00112
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piezoelectric member and connected to a first output; and a second electrode arranged on an opposite side of the piezoelectric member and connected to a second output, wherein the electrodes are offset so as to provide one or more regions in which the electrodes do not overlap, wherein both electrodes are discontinuous when viewed along a planar cross-section taken across the electrodes, and wherein the electrodes are arranged so that they can be cut in the non-overlapping region(s) without creating a short circuit between the electrodes and without breaking the connections with the first or second outputs.

By offsetting the electrodes, the capacitance between the electrodes is reduced. The capacitance can also be conveniently controlled by selecting a suitable amount of offset between the electrodes. Furthermore, an end user can cut the transducer in the non-overlapping region(s) without creating a short circuit between the electrodes.

In most cases there will be at least some overlap between the electrodes, but an end user can be directed not to cut in the region of overlap, for instance by providing suitable indicia on the transducer. Typically the total area of overlap is less than 50% of the total combined area of the electrodes.

One or both electrodes may be formed in a variety of patterns which are discontinuous when viewed along a planar cross-section taken through the electrode(s). For instance the electrodes may comprise rectangular grids which are diagonally offset from each other. Alternatively the electrodes may be formed in offset serpentine patterns. This has the advantage that overlap can be completely avoided if required. In a further alternative the first electrode comprises a plurality of fingers; and the second electrode comprises one or more fingers arranged between the fingers of the first electrode.

The capacitance between the electrodes can be controlled by varying the width of the interlocking fingers and their degree of overlap. The fingers may have different widths, or the fingers of the first electrode may have a width substantially equal to the width of the finger(s) of the second electrode.

The electrodes may have unequal areas. In this case the electrode with the larger area can act as an EMI shield.

The piezoelectric member may have a variety of shapes but in a preferred embodiment the piezoelectric member comprises a sheet and the electrodes are arranged on opposed major faces of the sheet. This enables the transducer to cover a wide area and the patterned electrodes cover a wider area per unit capacitance than conventional continuous electrodes. Typically the sheet is thin, with a distance of less than 0.3 mm (and typically less than 0.15 mm) between the electrodes.

In accordance with a second aspect of the present invention there is provided a method of shaping a transducer comprising a piezoelectric member which deforms in use to provide an electrical output; the method comprising manually cutting the transducer to a desired shape and size.

The second aspect of the present invention provides an end user with a convenient method of adapting the size and shape of a transducer (for instance using a knife or a pair of scissors) to enable the transducer to be accurately positioned in a desired location adjacent to a subject. The transducer may be adhered to the subject's skin but in a preferable embodiment the transducer is positioned by placing it in or on a subject support (such as a seat or bed) whereby when the subject occupies the support the transducer is able to pick up movement signals from the subject. Thus the end user can adapt the transducer to fit into irregularly shaped car seats, baby's prams etc.

Typically the piezoelectric member comprises a sheet, enabling the transducer to cover a wide area.

Typically the transducer comprises one or more electrodes which pick up the electrical output. In the cutting step, the end user may need to avoid

cutting through the electrodes in order to prevent a short circuit. Alternatively, a transducer according to the first aspect of the invention may be used, enabling the user to cut through the non-overlapping region(s) without risking a short circuit.

A further problem with conventional transducers is that the transducer connections are permanently connected via rivets or other means to external electronics. This makes it difficult to install the transducer.

According to a third aspect of the present invention there is provided a transducer comprising a piezoelectric member which deforms in use to provide an electrical output; first and second electrodes arranged on opposed sides of the piezoelectric member to pick up the electrical output; and a clamp for releasably securing the electrodes on each side of the piezoelectric member.

The transducer can be installed more easily by positioning it in a desired location with the electrodes detached, then securing the electrodes with the clamp. Furthermore, the clamp can be designed such that if, for example, the transducer is treated roughly by a child, the clamp will release the electrodes without causing any damage to the transducer. In a preferred embodiment the clamp is sprung so as to resiliently secure the electrodes.

Typically the piezoelectric member comprises a sheet and the electrodes are releasably secured on opposed major faces of the sheet.

The electrodes may connect ohmically with the piezoelectric member, either directly or via third and fourth electrodes (eg. layers of conductive ink adhered to the opposed sides of the piezoelectric member). In an alternative embodiment the first and second electrodes couple capacitively with the piezoelectric member (either directly or via the third and fourth

electrodes).

The first and second electrodes may be integral with the clamp (ie. the clamp may be electrically conducting). However in a preferred embodiment the clamp is made of an insulating material.

In the conventional monitoring system of US-A-5479932, an infant's large motor activities, breathing rate and heart rate are monitored. The system detects pulses, and if a new pulse is not received within a predetermined time interval, the system generates an anomaly signal. This is a fairly crude method of monitoring a subject.

In accordance with a fourth aspect of the present invention there is provided a method of monitoring a subject, the method comprising:

a) acquiring a movement signal from the subject;

b) extracting vital sign information from the movement signal, eg. cardiac or respiratory signals;

c) analyzing the vital sign information to determine the complexity of the vital sign information; and

d) generating an alarm signal when the complexity falls below a predetermined threshold.

In direct contrast with the conventional methods which generate alarm signals when a regular signal (eg. heart beat or respiration) becomes less regular (ie. increases in complexity) the present invention recognises that a certain level of complexity is desirable in a healthy subject. Therefore if the complexity falls below a predetermined threshold (indicating that the subject is entering into an unhealthy, anomalous pattern) an alarm signal is generated.

Typically the complexity is determined by determining the fractal dimension of the vital sign information. Examples of suitable analysis algorithms are

wavelet filter banks (ie. measuring how much energy is dispersed over different wavelet generations); Lempel-Ziv complexity measurements; and Lyapunov exponents. When the fractal dimension falls below a predetermined threshold (ie. indicating that the complexity of the movement signal is decreasing) an alarm signal is generated. Alternatively short-time Fourier transforms or Gabor expansion may be utilised – measuring how much energy is present in each bin and using standard deviation, peak measurements etc. Examples of suitable complexity measurements are described in Zhang et al, "Detecting Ventricular Tachycardia and Fibrillation by Complexity Measure", IEEE Transactions on Biomed Engg, Vo. 46, No.5, pp548-555, May '99.

In a preferred embodiment the piezoelectric member employed in each aspect of the invention is positioned adjacent to a flexible member (eg. a foam sheet), or the piezoelectric material may comprise a foamed mixture of a piezoelectric polymer and an elastomer.

Typically the piezoelectric material comprises a polymer such as polyvinylidene fluoride (PVDF) or one of its copolymers.

The transducers and methods of the present invention may be employed in a variety of applications. One application is monitoring of one or more vital signs (e.g. heartbeat, respiration). The transducer may be employed in infant sleep monitoring (in which an alarm is generated if the infant's sleep pattern becomes anomalous). Alternatively the transducer may be used to detect the state of wakefulness of the driver of a vehicle (in which an alarm is generated when the driver becomes drowsy). The transducer can be put on top of or into the driver's seat, and connected ohmically to the vehicle's power system and the alarm/monitor electronics.

Alternatively the transducer may be consciously manipulated by the user to provide active control of a device.

The invention will now be described by way of example with reference to the accompanying drawings in which:

Figure 1 shows a transducer and detector according to a first embodiment;

Figure 2 shows a transducer and detector according to a second embodiment;

Figure 3 shows the transducer of figure 1 in use;

Figure 4 shows a capacitive clamp connector;

Figure 5 is a plan view showing an electrode arrangement;

Figure 6 is a planar cross-section taken along line AA in figure 4;

Figure 7 is a planar cross-section taken along line BB in figure 4;

Figure 8 is a block diagram of a set of processing electronics;

Figure 9 shows a differential transducer;

Figure 10 shows an alternative set of processing electronics for the differential transducer; and

Figure 11 is a flow diagram of a method of generating an alarm signal.

Figure 1 shows a transducer in the form of a piezoelectric polymer sheet 1 sandwiched between flexible layers 3. Piezoelectric polymer sheet 1 may be formed of materials and by techniques known in the art. Layer 3 may be an elastomer foam having a density chosen to provide the required

deformation of polymer sheet 1 when a desired force is applied to piezoelectric polymer sheet 1.

Wires 4 are connected from electrodes 2, which are either printed or deposited on the polymer sheet 1, to detector electronics, 5. The layer 3 is adhered to the sheet 1 by a suitable glue. When sheet 1 is deformed a voltage develops across the sheet 2 related to the force applied to, and hence deformation of, the sheet.

The voltage from electrodes 2 is applied to detector electronics 5 which may generate an alarm signal when prescribed conditions exist.

Referring now to figure 2 an alternative construction is shown. In this embodiment the transducer is in the form of a piezoelectric polymer foam block. In this case a piezoelectric polymer is mixed with an elastomer and foamed to produce a resilient piezoelectric polymer foam block 6.

Wires 8 are connected to electrodes 7, such as wire or conductive plastic mesh, which are embedded in the foam during the manufacturing process of the piezoelectric polymer foam block 6, and detect voltages produced when forces are applied to piezoelectric polymer foam block 6, which deform it. The voltage across line 8 is monitored by detector 9 which again produces an alarm when prescribed motion conditions exist. The electrodes 7 are coated with non-conductive dielectric layers 17

Referring to figure 3, in use the transducer 1, 2, 3 is placed on a baby's bassinet 10, and the baby 11 placed on top of the transducer 1, 2, 3. As the child moves the deformation of piezoelectric polymer sheet 1 will cause the voltage between electrodes 2 to vary in relation to the changing forces applied to piezoelectric polymer sheet 1.

During manufacture of the piezoelectric polymer sheet 1 the sheet is

stretched along its length to pre-align the polymer molecules. The piezoelectric effect is then also enhanced, in all axes, by applying an electric field across the thickness of the sheet as it is cooling down. As a result, the charge generation of the molecules is as much as three orders of magnitude more effective along the length of the sheet (ie. by stretching/releasing along the alignment direction of the molecules) than across the thickness of the sheet.

Movements of the baby 11 cause the sheet 1 to flex and deform across the thickness of the transducer as indicated at 12 in figure 3. However by sandwiching the sheet 1 between the foam layers 3, this deformation 12 is converted into a lengthwise deformation indicated at 13. The lengthwise stretching 13 results in a higher voltage output than for the same force without the foam permitting extension. The same lengthwise stretching effect occurs when the transducer of figure 2 is used.

The density and thickness of the foam can be selected so as to result in the desired deformation of the transducer to produce the desired range of output voltages. One suitable piezoelectric polymer is PVDF (polyvinylidene fluoride) and its copolymers.

Figure 4 is a representation of a capacitive clamp engaged on the foamed version of the transducer shown in figure 2. The permanent electrodes 7 do not make an ohmic connection, but rely on a capacitive connection to releasable electrode plates 14 which are held in place by a non-conductive sprung clamp 15. The plates 14 are then ohmically connected via wires 16 to the signal processing electronics 9.

The clamp 15 can also logically hold any first level current amplifier circuitry required to reduce the susceptibility of the signal to electromagnetic noise during transport to the signal processing electronics.

The clamp 15 can be released by gripping the sheet, and sliding the clamp to the right as shown in Figure 4. Thus the transducer can be easily installed and the clamp will release without ripping the sheet if the transducer is treated roughly.

It will be appreciated that the electrodes 2,7 need not be contiguous conductive layers, but may be a pattern which does not occupy 100% of the surface of the polymer, or several isolated conductive patterns, such as used in keyboard applications or printed circuit applications.

An example of a suitable electrode pattern is shown in figures 5-7. An upper electrode and a lower electrode (shown in dashed lines in figure 5) are printed on opposite faces of a piezoelectric polymer sheet 29 which is sandwiched between protective layers 20. The upper electrode comprises five parallel fingers 22 connected to a strip 23 which is connected in turn to the cylindrical outer conductor 24 of a coaxial output cable 25. The lower electrode comprises five parallel fingers 26 connected to a strip 27 which is connected in turn to the central conductor 28 of the coaxial output cable 25. Alternatively the strips 23,27 may be connected to a capacitive clamp of the type shown in Figure 4.

The piezoelectric layer 29 is quite thin – typically 28-110 micrometers thick. As a result, if continuous electrodes are used, an electrical short may be created between the electrodes when a user cuts the transducer to size.

As shown in the planar cross-section of figure 6, the electrodes are discontinuous and the fingers 22,26 are offset from each other (ie. out of register which each other) when viewed along a line of sight perpendicular to the sheet. This minimises overlap between the electrodes and enables the transducer to be cut across the fingers without creating an electrical short. Similar advantages can be achieved with other patterns, such as

diagonally offset grid patterns or serpentine patterns.

In the cross-section of Figure 6 there is no overlap between the electrodes. There are also gap regions between the fingers (one of which is indicated at 50) where no electrode is present. Charge pickup is maximised by making the gap regions as small as the electrode lithography process permits (whilst maintaining no overlap between the fingers).

The fingers are shown with equal width in figure 6 but in an alternative configuration the lower fingers 26 are wider than the upper fingers 22. The increased area of the lower electrode gives an EMI shielding effect. In a preferred case the area of the lower electrode is greater than 95% of the total combined area of the two electrodes.

The user can be directed not to cut across the overlapping strips 23,27, for instance by putting a coloured stripe in the corresponding parts of the protective layers 20. Alternatively, overlap can be entirely avoided by positioning the strips 23,27 on opposite sides of the sheet.

The arrangement of figures 5-7 has a lower capacitance than an arrangement with continuous and/or non-offset electrodes. This results in an improved frequency response.

An example of an automatically calibrated movement detector electronics 5,9 is shown in figure 8. The signal from the transducer 30 via the releasable clamp 31 may be either differential from a two element transducer, or single ended, in which case one side of the transducer is grounded. The releasable clamp may have buffer amplifier circuitry incorporated in it, or all of the signal conditioning may be addressed in the signal conditioning electronics 32 of the main alarm assembly, which provides overvoltage protection, and analogue domain filtering suitable to

the environment in which the device is used, eg. low pass filtering, notch and/or comb filtering.

The conditioned signal is compared in Comparator 33 to a reference signal generated from a combination of a Pulse Width Modulator in the microcontroller device 34 and the following low pass filter 35. The reference threshold level for the comparator is controlled by the stored program or internal logic of the microcontroller device, which calibrates this threshold by a combination of averaging and minimum signal sampling, to set a stable, reliable threshold strongly correlated to the ambient electrical noise in the local environment.

The most simple example of a calibration routine is to have the end-user indicate via an input switch, when the transducer is not being activated (eg. a baby is not lying on it). While this switch is being held down, the microcontroller adjusts the duty cycle of the Pulse Width Modulator's digital output, so that the reference level produced by the low pass filter is just high enough to turn off the comparator output when the input is considered to be this transducer with no activity signal.

Alternatively, and preferably, a more intelligent automatic calibration scheme based on a long term averaging algorithm can be used to adjust the duty cycle of the Pulse Width Modulator during normal operation to arrive at a more flexible method of determining the ambient noise threshold, without the intervention of the end-user.

The low pass filter's 35 corner frequency is determined by the frequency of the Pulse Width Modulator's output.

It will be appreciated that the motion conditions which trigger an alarm may vary from case to case. In some cases the alarm may be triggered by detection of motion. In other cases the absence of motion at prescribed

times may actuate the alarm. Further, certain patterns, regular or irregular, may cause an alarm to be actuated.

Figure 9 illustrates a differential transducer. A pair of piezoelectric sheets 60,61, coated with electrodes 62-65 (which may be patterned and offset) are mounted between foam blocks 66-68. Electrodes 62, 65 are tied to local ground. Electrodes 63, 64 are applied to a differential amplifier configuration 69 such as an instrumentation amplifier. The transducer is placed with the upper sheet 60 adjacent to a subject. The upper sheet 60 deforms in response to movement from the subject. The lower sheet 61 does not deform as much as the upper sheet 60 in response to movement from the subject but is in substantially the same noise environment as the upper sheet. Therefore the differential signal 70 is a movement signal with the reference noise signal from the sheet 61 removed.

Figure 10 illustrates an alternative implementation of the signal processing required to isolate cardiac and respiratory signals from the differential transducer input. The target signal input 71 and the reference input 72 are processed through analog signal conditioning 73 to meet signal input limits. The processed versions are subtracted 75 from one another to remove ambient common mode noise signals, and then converted to digital signals 76. It can be appreciated that the analog – digital conversion may also be done before subtraction, allowing subtraction to take place in the digital domain. There are well known advantages and disadvantages to both approaches. Thereafter, the required digital processing 77, can be done. The extracted signal output is then either put directly onto a bus connecting to signal processing electronics 78 (eg. an automotive electronics interface), or else drives a display interface directly, or both.

In one example the digital signal processor 77 implements the process illustrated in figure 11. At step 39 the processor extracts vital sign information from the movement signal, eg. by a suitable filter algorithm

which extracts cardiac, respiratory signals etc. At step 40 the processor analyses the complexity of the vital sign information over a predetermined period. A variety of algorithms may be employed, including: wavelet filter banks (how much energy is dispersed over different wavelet generations); short-time Fourier transforms/Gabor expansion – similar to above – how much energy in each bin, eg. standard deviation, peaks etc; Lempel-Ziv complexity measure; and Lyapunov exponents.

The level of complexity is compared to a predetermined threshold in step 41. If the complexity drops below the threshold, an alarm is generated at 42. Otherwise the process returns to step 40.

Where in the foregoing description reference has been made to integers and elements having known equivalents, then such equivalents are incorporated as if individually set forth.

Although this invention has been described by way of example and with reference to possible embodiments thereof, it is to be understood that modifications and improvements may be made without departing from the spirit or scope of the invention.